Malaysian Journal of Chemical Engineering & Technology 6(2) (2023) 88–97

Malaysian Journal of Chemical Engineering & Technology

Journal Homepage: http://myjms.mohe.gov.my/index.php/mjcet

e-ISSN: 2682-8588

Recent advances on microplastics/nanoplastics interaction with plant species: A concise review

Nurfarwizah Adzuan Hafiz, Nurin Nabilah Jalaudin Basha, Mohamed Syazwan Osman *

EMZI Nanoparticles Colloids & Interface Industrial Research Laboratory (EMZI NANO-CORE)
Chemical Engineering Studies, College of Engineering, Universiti Teknologi MARA (UiTM) Cawangan Pulau Pinang, Kampus Permatang Pauh, 13500 Permatang Pauh, Pulau Pinang, Malaysia.

*Corresponding email: syazwan.osman@uitm.edu.my

Abstract

The transmission, toxicity, and removal of micro/nanoplastics (MPs/NPs) have been the subject of extensive attention and have impacted concerns globally. The inclusion of microplastic pollution can have a plethora of effects on plant growth, depending on the composition of the planting media. Following a recent year of research focusing mostly on aquatic systems, attention has begun shifted to the consequences of microplastic on plant cells. Therefore, there is a significant knowledge gap regarding the extent to which MPs have an impact on terrestrial environments, particularly agroecosystems, and the risks that this has for human health. Within this review, the interaction of MPs/NPs to plant species is due to the abundance of microplastics in soil following human activity. This review also summarised the routes of MPs/NPs to the plant through the root and shoot of the plant. Subsequently, the emergence of MPs/NPs influences and brings implications on plant growth, growth, and crop production according to each plant species. Besides, the recommendations for further research on the phytotoxic effects of MPs on plants, the method of uptake and translocation in plant tissues, detection techniques for MPs in plants, and, most importantly, the potential for future interactions and accumulation of MPs in plants have also been discussed thoroughly in this paper. The most recent developments in this area are summarised at the end, with an emphasis on the future directions for studying microplastics in terrestrial systems.

Article Info

https://doi.org/10.24191/mjcet.v6i2.22497

Article history:

Received date: 26 May 2023
Accepted date: 8 September 2023
Published date: 31 October 2023

Keywords:

Microplastic
Phyto-toxic
Plant extract
Nanoparticles
Nanotechnology

1.0 Introduction

The overabundance of residing microplastic (MPs) particles has been steadily increasing since 2005, according to annual global estimations based on contaminants from 1979 to 2019. These new contaminants are overproduced and released into the environment as a result of the excessive demand for and consumption of goods or technology containing microplastics. The quality of the soil for terrestrial plants and the availability of water resources and its quality for aquatic plants have a significant effect on the development and growth of plants. Plants are complex and highly dynamic, in addition to being completely dependent on their environment.

The majority of the 12,000 Mt of plastic garbage that will end up in landfills by the year 2050 is predicted to be packaging debris (Chamas et al., 2020). Plastic waste that is discharged into the environment is transformed into MPs via thermal breakdown, physical abrasion, exposure to ultraviolet radiation, wind, etc., and accumulates in both aquatic and terrestrial ecosystems, including agricultural fields (Ng et al., 2018a; Zhu et al., 2019).

Studying MPs accumulation in marine environments and their transportation, distribution, and effects on aquatic animals has received a lot of attention in recent years. Despite being ubiquitous in soils, little is known regarding their persistence and quantification in terrestrial ecosystems (Bläsing & Amelung, 2018; Rochman, 2018; Windsor et al., 2019). As microplastics include a variety of potentially toxic chemicals, they can directly affect soil biota (Kim et al., 2020; Lehmann et al., 2022). Associated with agricultural activities, including the amendment of soil via sewage/sludge and organic fertilizers, including the usage of plastic films and mulches, soil systems have developed into a significant sink for plastics (Chae & An, 2018; de Souza MacHado et al., 2018; He et al., 2018). MPs are often characterised as plastic particles less than 5 mm (Mhiret Gela & Aragaw, 2022). The smallest fraction of MPs classified as nanoplastics (NPs) are plastics with a size of less than 100 nm or 1,000 nm, with the lower size restriction being the subject of academic discussion (Gigault et al., 2018).

The health care system, biotechnology, and textile sectors have created or enhanced technologies that includes nano-based vaccine, sensors for the detection of virus infections, and supplies to stop the infection and transmission of COVID-19 in people. This is particularly valid due to the massive continuing COVID-19 pandemic, which has dramatically boosted the demand for microplastics (Ardusso et al., 2021; Campos et al., 2020; He et al., 2018). Certain microplastics, such as those built on Cu and Ag, have powerful antibacterial capabilities and have been used in commercial products to reduce the risk of viruses, particularly SARS-CoV-2. However, since MPs/NPs from several industrial products, such as for antiviral paints and textiles, could have a harmful impact on aquatic habitats and plant species, which is the main cause for concern (Hashmi & Strezov, 2022; Mohan et al., 2019; Zuin et al., 2014). Due to their inherent characteristics (e.g., size range, variability in component chemistry), as well as their change through time in the plant media, these micro/nanomaterial contaminants have been among the most difficult to remove, identify, and characterise for the scientific community. The interaction of hazardous substances of MPs/NPs to plant species in agricultural system has not yet been thoroughly studied by many experts (Ng et al., 2018b).

Although the sea ecology is contaminated with microplastic, the terrestrial environment is much more. This is due to terrestrial ecosystems producing and using more plastic. Additionally, soil acts as a storage area for environmental degradation, including 4 to 23 times more microplastic (MP) contamination than aquatic ecosystems (Mitrano & Wohlleben, 2020). MPs in agriculture are seen as a severe problem in terms of the agricultural production system considering that they might directly affect the resilience and health of the soil. This mini review provides a summary of the diverse research on microplastics and nanoplastics plant species, specifically on the routes taken by the MPs to the cell of the plant, the studies and impact of MPs to the growth and nutritional quality of the plant species. Although there is a lot of pertinent literature, some of it has fortunately been covered recently, and this summary will briefly touch on it.

2.0 Scope

Within this review, the interaction of MPs/NPs to plant species is due to the abundance of microplastics in soil following human activity. This review also summarised the routes of MPs/NPs to the plant through the root and shoot of the plant. Subsequently, the emergence of MPs/NPs influences and brings implications on plant growth, growth, and crop production according to each plant species. Besides, the recommendations for further research on the phytotoxic effects of MPs on plants, the method of uptake and translocation in plant tissues, detection techniques for MPs in plants, and, most importantly, the potential for future interactions and accumulation of MPs in plants have also been discussed thoroughly in this paper.

3.0 Trends in the studies on MP/NP plant interaction

In this systematic literature review, based on our search on the keywords, twenty-four articles that fulfilled the keywords interaction of MPs/NPs to plants were selected and reviewed in this work. The initial study was released in 2018; since then, this new field of study has drawn more interest and published research publications in 2021. Most plastics are environmentally permanent and are anticipated to accrue in soil, which is probable to occur in MP concentrations in soil that are constantly rising. According to recent studies, microplastic can affect microbial community diversity and activity, soil characteristics, plant performance, and other factors (Boots et al., 2019; de Souza MacHado et al., 2018). Given the increasing prevalence and use of plastic pollution on a global basis, this tendency will probably keep developing.

Following the trends in this field, China, one of the world's greatest manufacturers and suppliers of plastic, has been proactively involved in the study of aquatic microplastics (Wang et al., 2022). Consequently, there are significant worries about MPs particles that have already gone beyond specialised scientific research to significant pollution control and global governance. Pollution driven on by plastic debris has also started to emerge as a political issue that is interconnected with ecological and sustainability economic concerns (Jiang et al., 2020). The important connections between various plastic materials and species of plants have also been highlighted in publications from other nations like the Netherlands, Germany, Italy, Norway, and United Kingdom (Amrutha et al., 2021).

4.0 Sources and distribution of microplastics in plants

The studies from Padervand indicate that the primary sources of MPs/NPs are acknowledged to be freshwaters and terrestrial habitats, while the sea and ocean are the significant sinks (Padervand et al., 2020). Most MP sources are caused by human activity, such as the direct landfilling of plastic bags, dumped fishing nets, polyurethane foam, and other disposable plastic resources (Karthik et al., 2018). Also, due to unexpected, incomplete burning, and lack of appropriate plastic management practices, MPs are also transferred and moved from one place to another (Irfan et al., 2020; Patchaiyappan et al., 2020).

All the primary and majority sources of MPs, in the end, are transferred to the ocean, atmosphere, and soil. Hence, in this study, in the aspect of MPs abundance in soil, consequently affecting the plant species. Early studies did, in fact, reveal that soil-derived particles are present in the MPs/NPs trash that makes its way into rivers and the ocean. Considering that there are high concentrations of MPs/NPs in some terrestrial and aquatic environments, this indicates that soils and freshwaters are also sources for MPs/NPs. Agricultural and forest soils are more capable of retaining microplastics than urban areas due to the long-term durability of microplastic fibers found in deeper layers (25 cm) of agricultural soils treated with sewage sludge as fertilizer (Ullah et al., 2021). This suggests incremental transport in solid media, followed by further accumulation at depth.

According to Mason et al., MPs from waste produced by industrial facilities, wastewater treatment facilities, and municipal solid trash may entangle with various terrestrial and freshwater species and result in fatalities (Mason et al., 2016). When manufactured NPs are discharged into the atmosphere, these particles may harm plants for food by migrating into the water and soil, having an impact on the entire food chain. Therefore, NPs ought to be considered a "new" variety of pollutants that could seriously endanger the ecosystem. It is vital to examine their possible toxicity and environmental fate using the right risk assessment techniques.

5.0 Routes of microplastic to plant

The disposal of industrial effluents wastewater, landfills, urban and agricultural runoff, sewage spills, and combined sewer flows have all been identified as the primary entry points for NPs into the environment (Wahl et al., 2021). MPs get through soils by irrigation, mulching with plastic, irrigation, diffuse urban runoff flooding, and airborne fallout (Qi et al., 2018). As a result, soil may include concentrations of microplastics up to 7% close to industrial areas in the form of fibers, films, or granules with a variety of shape, content, and abundance (Lozano & Rillig, 2020). Studies by Li et al. (2020) indicate that plastic debris enters the primary and secondary roots of wheat's epidermal tissue, where they stimulation occurs through the pericycle and transferred into the xylem. These particles can migrate to the aerial portion of the crop through the xylem within the central cylinder. The vascular system moved plastic debris from the root to the shoot via the process of transpiration. MPs and NPs can enter the vasculature which is accountable for transporting water by passing through small extracellular routes. The stem, leaves, and potentially fruits can swiftly absorb the water transport system that supports NPs.

MPs are more likely to agglomerate and become adsorbed onto plant tissue compared to NPs, which can enter plants through pores or the stomata despite their smaller size. According to research by Sun et al. (2021) stomatal penetration is one potential route by which NPs enter the leaves and then proceed to the vasculature. These findings demonstrate NP transport throughout the vascular bundle from the leaves to the stems and then from the stems to the roots. Presently, only a very small number of MPs and NPs are being absorbed and accumulated in the plant shoot. The processes of MP and NP absorption and transportation in plant shoots need to be further studied.

The plastic polymer will also have an impact on how tightly MPs adhere to leaves. Some MPs can be particularly challenging to extract from agricultural crops like lettuce, regardless of washing with water, due to the charge on the outer layer of plastic and the bonds of chemicals between the MP and the surface of the leaf. Condescendingly charged mucilage and exudates, which serve as the first line of defence in plants, have been found to prevent positively charged metal NPs from adhering to the outside of the cellular wall (Azeem et al., 2021). Thus, the consequences of MP on agricultural systems vary depending on the type of MP and the plant-soil combination at operation. For instance, MP films would have a significant impact on agricultural areas due to the extensive use of plastic mulching to increase plant production, whereas microfibers would typically have a greater impact on rivers or roadside vegetation (Sommer et al., 2018). Fig. 1 represents the pathways of MPs/NPs association, uptake, and translocation in plants through shoot and root.

6.0 The effects of microplastics

6.1 Influence of microplastic (general) towards growth and nutrient quality

MPs have been demonstrated to influence plant growth performance in some types, such as harvests or crops growing as single individuals or in populations, but not in a broader community. Numerous physiological responses, including germination, root length, plant height, shoot biomass, and root growth under stress exposure, are regarded as signifiers of plant growth (Füzy et al., 2019; Lian et al., 2020). The current research supports the notion that exposure to different MPs/NPs can have a detrimental effect on plant species (Mateos-Cárdenas et al., 2021). For instance, *Triticum aestivum* (wheat) and *Lolium perenne* (grass) subjected to films or fibers both demonstrated decreased biomass (Boots et al., 2019), whereas *Allium fistulosum* (crop) had the reverse result (de Souza Machado et al., 2019). In terms of root morphological features, *Plantago lanceolata* (a forb) as well as *Allium fistulosum* responded to microplastics differently (e.g., root length) (van Kleunen et al., 2020).

Theoretically, MPs are considered as physiological pollutant of soil and preliminary findings indicate that it does indeed result in a significant decrease in soil bulk density. This could directly translate to improved soil aeration and less resistance to plant root penetration, leading to greater root growth (Chen et al., 2022). It has been demonstrated that plastic films (2-, 5-, and 10-mm size pieces added at 0.5% and 1.0%) generate channels for water circulation, increasing water evaporation. This can induce the soil to dry up, which might have an adverse effect on how well plants grow. Moisture in the soil tension has subsequent or long-term impacts on cell elongation and growth, cellular and metabolic activity, photosynthetic suppression, turgor loss, reactive oxygen species production and altered carbon partitioning (de Souza Machado et al., 2019).

The overall findings of the meta-analysis demonstrated that MPs/NPs had an impact on physiological end points. Shoot biomass and root length were lowered by about 25%, with other

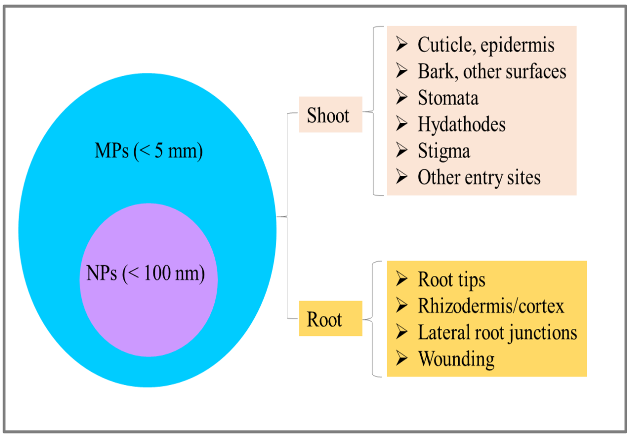

Fig. 1: Pathways of MPs/NPs association, uptake, and translocation in plants through shoot and root (Source: Author’s illustration)

reductions being noticeable for germination (13%) and root biomass (13%) and plant height (6%) (Azeem et al., 2022). *Lepidium sativum* seedling growth was negatively impacted by both MPs and NPs, when exposed to MPs (4800 nm), only 21% of the seeds germinated, but 56% did so when exposed to NPs (50 nm) (Bosker et al., 2019). When exposed to MPs at 1.0 g/kg, the germination of *Lolium perenne* (grass) was reduced by 9 and 8%, correspondingly. In conclusion, the results of the meta-analysis demonstrate that NPs have a more detrimental impact on root and shoot biomasses compared to MPs. These studies are also supported by van Weert et al., as the primary shoot length of *Myriophyllum spicatum* was also reduced by nanoplastic, but shoot biomass was unaffected (van Weert et al., 2019). Hence, this can be said that the negative effect of NPs on root length and shoot biomass is depending on the plant species.

6.2 Influence of shape of microplastics to plants growth

In order to distinguish MPs from combinations of inorganic and organic residual particles, physical features (size, shape, and colour) and chemical characteristics (polymer type) of isolated particles have been used. MPs are still difficult to analyse quantitatively because of their decent and small size. Following their morphology, different forms of MP may be recognised, such as predominant MP, which is constructed of spheres (beads, pellets, and granules) and secondary MP, which is made up of fibers (filaments and lines), films, fragments, and foams (Karami et al., 2018). These components will respond differently in the surroundings and impact terrestrial ecosystems in diverse ways. For instance, the addition of microfibers (at concentrations ranging between

0.05 % to 0.40%) appears to have a stronger effect on the physical characteristics of soil than the addition of beads (which were added at concentrations between 0.25 to 2.00%) (de Souza MacHado et al., 2018). As shown in Table 1, we also included microfibers and, more significantly, biodegradable materials (Qi et al., 2018), films (Wan et al., 2019), and nanoscale materials.

In accordance with previous research, Lozano et al., attempted 12 MPs of various shapes (fibers, films, foams, and fragments) and polymers and combined them with soil at concentrations of 0.1, 0.2, 0.3, and 0.4% (Lozano & Rillig, 2020). In each medium, a phytometer (*Daucus carota*) grew for four weeks. Measurements were made of microbial activity, soil aggregation, shoot, root, and root mass. Plant biomass ascended in all forms. Shoot mass enhanced with fibres by 27%, films by 60%, foams by 45%, and fragments by 54%. Fibers keep water in the soil for a longer period, films reduce soil bulk density, foams and fragments can boost soil aeration and microporosity, which in turn improve performance of the plant. From this research, we found out that MPs do have advantages to a certain species of plant.

Additionally, it was shown that the size of microplastics was significantly associated to their toxicity (Gonçalves & Bebianno, 2021). In terms of behaviour, the more hazardous the particulates are to the species, the finer the particle size (Ge et al., 2021a). The relative abundance of each size group may be greatly impacted by various size categorisation standards used in different research. Furthermore, the measurement method for irregular objects may differ between research, and this inconsistency may have an impact on the numbers in each size group.

According to study, at the very least, particle size and shape will have highly distinct effects on plant growth and may potentially raise different questions about consumer safety. Similar theories might also be put out for various MP chemistries and other factors when more information and data is acquired (particularly surface characteristics). Therefore, standardised methods for measuring and showing the size distribution of microplastic particles are urgently required to properly utilise the size distribution data.

7.0 Toxicity of microplastic through plants

Plants growing in agricultural soils are constantly exposed to MPs when plastic mulching, sewage sludge as fertilizer, and organic composted manure are used (Watteau et al., 2018). This variability of particular response of plants allows for the possibility that the presence of MPs to the soil may have varying effects on various plant species within a community, which may have an influence on plant yield and ecosystem processes (de Souza Machado et al., 2019). As a result, some species within a community would be better equipped to benefit from the modifications in soil characteristics brought on by the accumulation of microplastics.

MPs in the substrate circulate and build in crops are then carried to consumers via the food chain, endangering both human wellness and the natural environment (Ge et al., 2021b). The main cause for agricultural toxicity is MP/NP adsorption and uptake through root tips. Since MPs/NPs have a detrimental influence on the growth and maturity of plants, crops that are cultivated in soil that contains contaminants with plastic debris or that is irrigated with sewage represent a threat. Additionally, in densely populated

Table 1: The impacts of various microplastic particle types on plants are hypothesised, as are agricultural safety issues

Shape of MPs	Major hypothesised effect pathway	Expected effect size for the growth of the plants	Ref.
Beads, fragments	Minor changes in soil texture.	Minor	(Rillig et al., 2019)
Fibers	Soil structure, bulk density changes, and increased in shoot mass by 25%.	Large	(de Souza MacHado et al., 2018)
Films	Increased soil water evaporation and in shoot mass by 60%.	Intermediate to large	(Qi et al., 2018)
Biodegradable	Nutrient immobilisation in soil (short-term) hence decreased in nutrient contents.	Intermediate	(Wan et al., 2019)
Nanoplastic	Toxicity in plant roots and soil microbiota.	Minimal to intermediate	(Awet et al., 2018)
Foams	Increased in shoot mass by 45%.	Intermediate	(Lozano & Rillig, 2020)
Fragments	Increased in shoot mass by 54%.	Intermediate	(Lozano & Rillig, 2020)

and industrial locations, there is a higher danger of airborne deposition of MPs/NPs on different plant components.

Recent research has examined the effects of MPs/NPs exposure on several crop species, and the results have ranged from neutral effects to overt phytotoxicity (Bosker et al., 2019; Kalčíková et al., 2017; Qi et al., 2018; van Weert et al., 2019). MPs harm the community in two different ways. One is that MPs act as transporters by absorbing harmful substances from the environment. The second is the addition of hazardous chemicals to MPs to increase their elastic properties and extend their shelf life (Bhagat et al., 2021).

Studies conducted in vitro and in vivo revealed that MPs/NPs ingested by humans concentrate in the intestinal lumen, while some of these polymers are expelled through faeces (Lai et al., 2022). According to results from research on animals, nanoparticles dispersed in the intestinal lumen have the ability to cross the intestinal barrier and then travel to the arteries (Alqahtani et al., 2023). Nanoplastics can breach the blood-brain barrier and cause fish to suffer brain injury, as demonstrated by research conducted on NPs that were ingested through the food chain (Lai et al., 2022; Yee et al., 2021).

Cell destruction and harm to membrane structure are two serious consequences associated with biological interactions. This process depends on many variables, including kind and surface charge. For instance, polyethylene nanoparticles combine with the hydrophobic centre of lipid bilayers to create a network of loosely connected single polymeric chains (Hollóczki & Gehrke, 2020). These complexes encourage damage to the permeability and structure of the membrane, which ultimately leads to cell demise. Numerous interactions between polystyrene particles with amino alterations and cellular membranes lead to abnormalities in ion transport, signal transduction, membrane integrity, and occasionally cell death (Qu et al., 2019).

The most common additives employed in the plastics industry, their destiny after MPs is discharged into the environment, and their ensuing consequences on human health when linked to micro and nanoplastics are all unknown yet. The absorption of these NPs by plants is inversely associated with their particle size and could have a negative impact on plant growth and agricultural productivity. In recent years, researchers have focused on the significant risk to human health from the presence of microplastics and nanoplastics in consumable fruits and vegetables.

8.0 Future outlook and challenges

This analysis identifies many significant knowledge gaps regarding the behaviour of soil-borne microplastics and nanoplastics and their ecological impacts. The following is a concise summary of several significant challenges. There is little concern given to MPs that people may consume through food or drink, especially through the farming of plant species, and that may build up in the body, harming their organs and increasing their risk of death (Karthik et al., 2018; Vidyasakar et al., 2018).

Additional research was required into the impact of MPs on the physicochemical characteristics of soil. The physical impacts of MPs on the soil have only been the subject of a small amount of research. A wide spectrum of MPs in various soil types should be taken into mind when this issue is further developed. It is important to consider the biological effects of MPs on the microbial communities they are contained in, as well as the biological effects of MPs themselves.

As mentioned earlier, the toxicity of microplastics was strongly correlated with their size. Hence this indicates that nanoplastics will uncertainly bring more threats compared to microplastic due to its finer particles. The entire food chain may be affected by the harmful effects of produced nanoparticles that are released into the atmosphere and migrate into the water and soil, harming plants that are used as food. Nanoparticles should be regarded as a "new" type of contaminant that poses a major threat to the environment. It is critical to use the appropriate risk assessment tools to investigate their potential toxicity and environmental consequences.

9.0 Conclusions

The researchers have taken a keen interest in micro/nanomaterial contaminants due to their various extrinsic and intrinsic qualities, special aquatic behaviour, and possible harm to ecosystems, wildlife, and human health. The influence of nanoparticles on various plants varies considerably, and both advantages and disadvantages effects have been documented, depending on species of plants and nanoparticle nature/composition, size, concentration, and exposure time. However, it was discovered that different characteristics of nanoparticles had a detrimental impact on plant biomass, root elongation, and seed germination rates (Jha, 2018).

Since there is very little that can be done to minimise the dispersion and effects of MPs once they are exposed to the environment, restricting MPs/plastics at the source is an alternative that needs to be actively considered. The abundance is not correctly quantified by the one-day sampling. Consequently, a few repetitions from several sites after an equal amount of time would help to refine the data regarding plants sampling (Saliu et al., 2018).

Accuracy and precision are achieved through the development of sound methodologies and their fusion with all other genuine procedures. Through consuming, MPs seriously endanger both marine and terrestrial life. Due to its resemblance to food particles, particularly in this context, the vegetables, and biomagnifies from lower trophic level to higher trophic level, it enters the food chain of living. To enhance waste management practises and local bodies on a small scale, more studies into MPs and their connections to other impurities will also be conducted. Most significantly, government initiatives and non-governmental organisations should promote public knowledge and awareness to use biodegradable packaging and other non-plastic materials, and stringent laws should be revised to avoid any violation.

Contribution statement

Nurfarwizah Adzuan Hafiz: Methodology, software utilization, formal analysis, investigation, data curation and writing-original draft; **Nurin Nabilah Jalaudin Basha**: Conceptualisation, writing- review and editing, and visualization. **Mohamed Syazwan Osman**: Writing-review & editing, conceptualisation, supervision, project administration and resources.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research work was supported by the Ministry of Higher Education Malaysia through the Fundamental Research Grant Scheme (Grant No FRGS//1/2022/STG05/UITM/02/10)). We acknowledge EMZI-UiTM Nanoparticles Colloids & Interface Industrial Research Laboratory (EMZI NANO-CORE) for the facilities support provided for this work.

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